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CEMENTING THROUGH PERMAFROST ENVIRONMENT

by W.C. Cunningham
D.K. Smith

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Cementing Through Permafrost Environment

W. C. CUNNINGHAM

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Haliburton Services,
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Cold ambient temperatures of subarctic areas combined with cool subsurface temperatures at conductor and surface pipe depths cause undesirable and expensive Waiting-On-Cement time. Further north in the Arctic regions of permanently frozen (Permafrost) shallow zones, more troublesome cementing problems may occur. This paper discusses materials and techniques for avoiding extended WOC time in subArctic areas by judicious acceleration of the cement, utilizing the high early strength development of densified cement and displacing with a warmed fluid. The paper gives data for a special cementing formulation for the troublesome Permafrost formations of the Arctic and gives the benefits of this cement for Arctic cementing. A study of cementing conditions in the Arctic combined with the cooperative testing of many laboratories produced a standard API testing laboratory procedure for Arctic cementing materials.

Contributed by the Petroleum Division of The American Society of Mechanical Engineers for presentation at the Energy Technology Conference and Exhibit, Houston, Texas, September 18-22, 1977. Manuscript received at ASME Headquarters June 13, 1977.

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Cementing Through Permafrost Environment

W. C. CUNNINGHAM D. K. SMITH

INTRODUCTION

Field operators and engineers in the northern tier of states of the Continental United States and the southern provinces of Canada frequently experience expensive, unproductive waiting-on-cement time. The area of greatest concern has been surface casing cementing; this is due to the difficulties caused by the low temperature curing conditions. It may generally be accepted that formation temperatures at surface casing depths equal the mean surface temperature plus 2 F (1.1 C) per 100 ft (30.48 m) of depth. The mean surface temperature is 40 F (4.4 C) at the U. S. border and steadily decreases as one proceeds north until it reaches approximately 25 F (-3.9 C) at the boundary of the Northwest Territories.

Thirty years ago it was recognized that cements needed very little strength in order to support a string of casing (1, 2, 3).[1] A cement possessing a tensile strength as low as 8 psi (0.564 kg/cm^2) appeared adequate. Later work supported these conclusions, and data obtained showed that a 10-ft long (3.05 m) annular sheath of cement with a tensile strength of 8 psi (0.564 kg/cm^2) would support more than 200 ft (60.96 m) of casing in the lighter weights of the casing sizes commonly in field use.

Cement strength testing in recent years is being performed in compression rather than tension. As a general rule, the former is approximately ten times as great as the latter; thus, for simplicity assume that 8 psi (0.564 kg/cm^2) tensile strength is equivalent to 100 psi (7.05 kg/cm^2) compressive strength.

Due to variations in procedures, materials, and curing temperatures, conditions cannot be sufficiently controlled or known in the field to be able to establish the curing time required to obtain this minimum strength without encountering the possibility that the cement may not be set at all. Therefore, a reasonable safety factor should be applied. It is generally accepted in the industry that a compressive strength of 500 psi (35.3 kg/cm^2) is adequate for most operations, and, with diligent practice, an operator should be able to safely drill out using an established minimum strength of 250 psi (17.6 kg/cm^2).

Figs. 1 and 2 illustrate the curing times required for the commonly available cements to develop a compressive strength of 250 psi

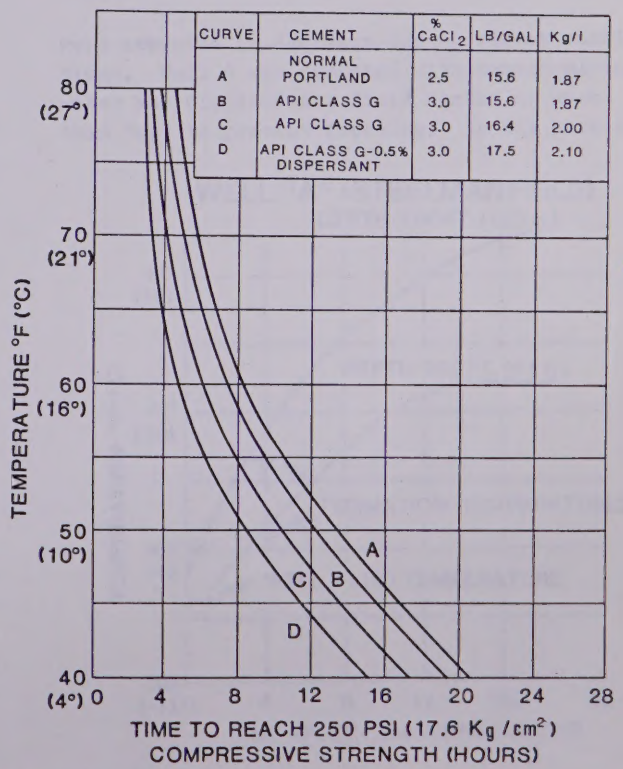
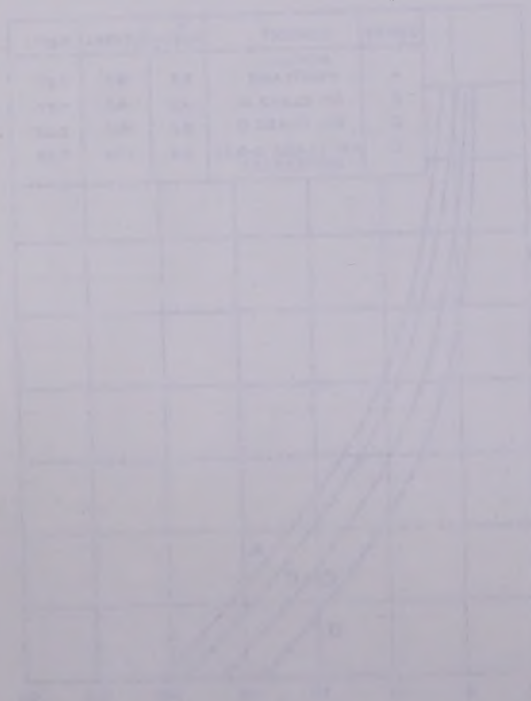


Fig. 1

[1] Numbers in parentheses designate References at end of paper.



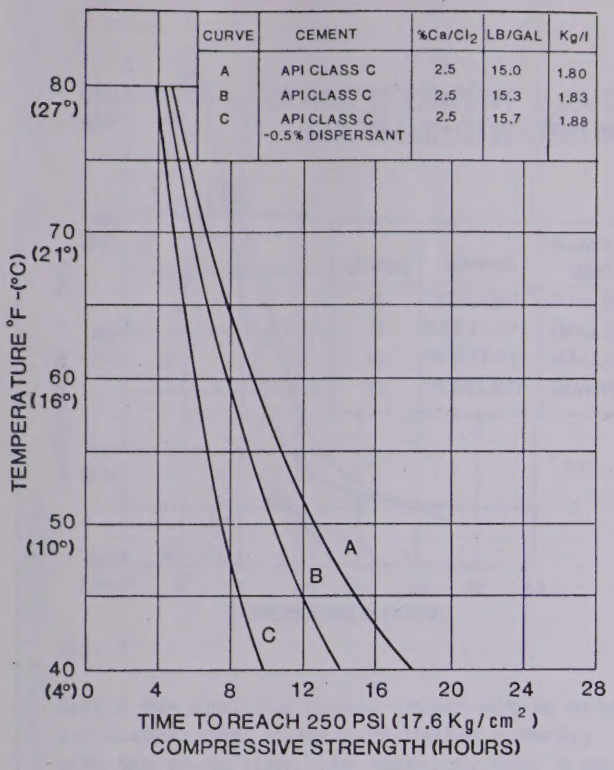


Fig. 2

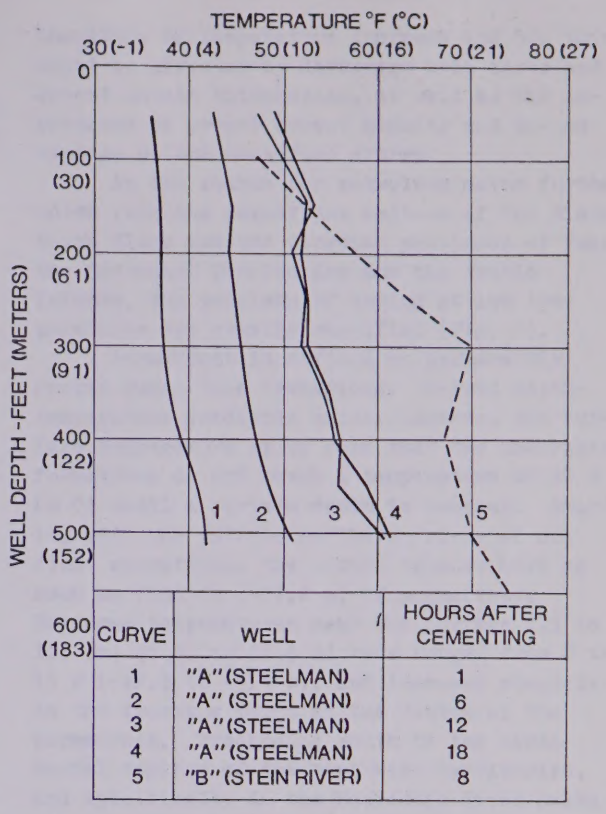


Fig. 3

(17.6 kg/cm^2) at temperatures varying from 40 F (4.4 C) to 80 F (26.7 C). Note that for the Oilwell (API Class G) and High Early (API Class C) cement, curves are given for three different water ratios. The introduction of dispersants to thin the slurry allows a reduction in the water-cement ratio and produces a significant increase in early compressive strength which may be used to advantage in reducing WOC time (4). The optimum calcium chloride concentration has been found to be from 2.5 to 3.0 percent. Such slurries yield slightly higher compressive strengths than those mixed with the customary 2 percent.

It is obvious from the compressive strength plots that curing temperature is a most significant factor in strength development. Static bottom-hole temperatures have been reasonably well defined by the application of surface isotherm data coupled with the accepted depth-temperature gradients and verified by temperature surveys conducted in uncased surface holes.

Cement curing temperatures were recorded at various depths and times inside the surface casing after the cement was placed. Fig. 3 illustrates two typical temperature profiles which were obtained. Both Well A and Well B were cemented in February during winter conditions. Well A was cemented with cement mixing water and displacement fluid heated no more than just to prevent freezing. In the case of

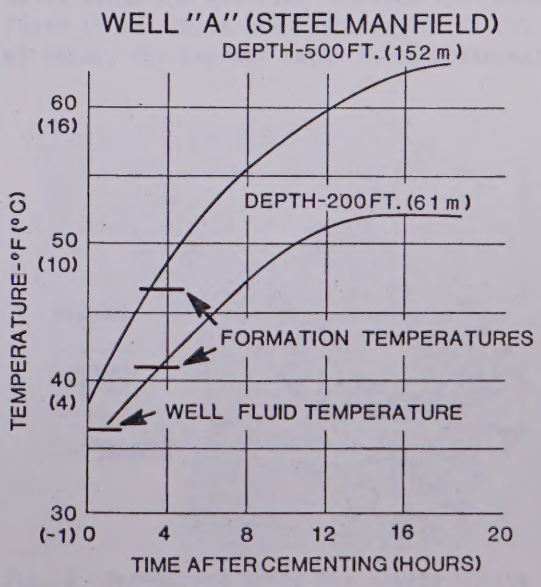
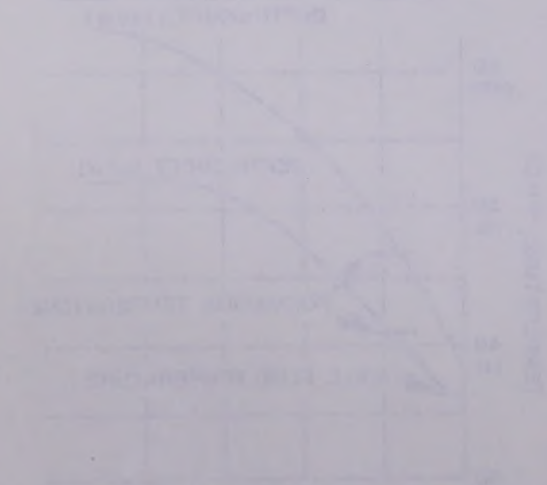


Fig. 4



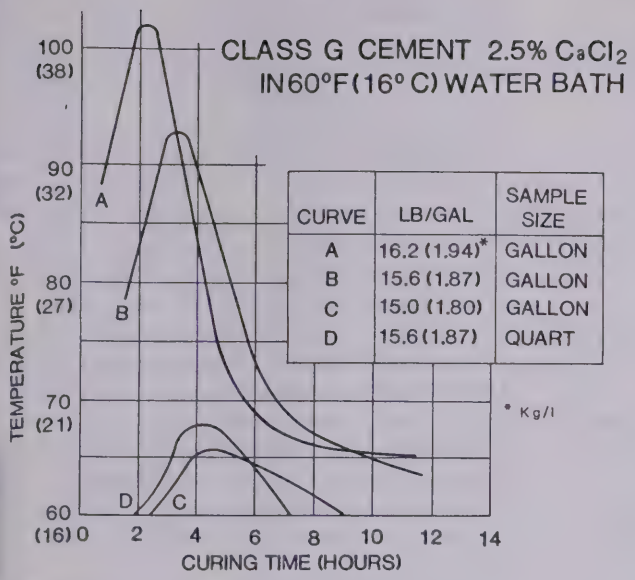


Fig. 5

Well B the drilling fluid, cement mixing water and displacement water were heated normally with the steam line. As expected, Well B had considerably higher curing temperature conditions than Well A; however, at a depth of 500 ft (152.4 m), the average curing temperature for Well A over the first 12 hr was approximately 50 F (10 C) and over the first 18 hr it was approximately 55 F (12.8 C).

The increasing temperature with time exhibited by Well A is caused by the heat of the hydration (Fig. 4). Laboratory investigation into the heat of hydration showed three effects pertinent to low temperature cementing:

1 The densified or low water ratio slurry produced more heat.
2 The larger size samples produced more heat.
3 Samples cured at 40 F (4.4 C) indicated no temperature rise showing the hydration reaction occurred at a constant 40 F (4.4 C).

The temperature data from the 60 F (15.6 C) test are plotted as Fig. 5. Since no attempt was made to simulate well-bore geometry, and the circulating, refrigerated bath used to simulate a constant bottom hole temperature is probably a more efficient heat transfer medium than most formations, the data are not directly applicable for estimating curing temperatures. They do give an indication of the order of magnitude of temperature increase and how this might be affected by different hole sizes and cement sheath thicknesses, as well as the importance of proper cement density and the advantage of the densified slurry.

As the search for petroleum moves further north into the permafrost regions of the Alaskan North Slope and the Canadian provinces of Yukon, the Northwest Territories and the Arctic Islands, the problems of curing at low temperatures are greatly magnified (Fig. 6).

Permafrost is defined as permanently frozen subsurface formations. Normal depth-temperature gradients exist; however, the surface temperature is so cold that the underlying formations do not reach a temperature of 32 F (0 C) until a certain depth is reached. Starting with the extreme northern fringe of oil field operations, the Arctic Islands have as much as 1500 ft (457.2 m) of permafrost. Measured temperatures near the surface (25 to 100 ft) (7.62 to 30.5 m) have ranged from 8 to 15 F (-13.3 to -9.4 C), and increase steadily to the freezing point at the bottom of the permafrost. Proceeding south to the continental regions of the Northwest Territories, and specifically in the Mackenzie River Delta area, the permafrost is approximately 300 ft (9.14 m) thick, with shallow subsurface temperatures of 22 to 25 F (5.6 to 3.9 C).

In the Mackenzie River Delta and other continental regions, including the Alaskan North Slope, the shallow formations consist of ice lenses, frozen muskeg and unconsolidated sands and gravels. Whereas the permafrost in the Mackenzie Delta is 300 ft (91.4 m) thick, the average depth is approximately

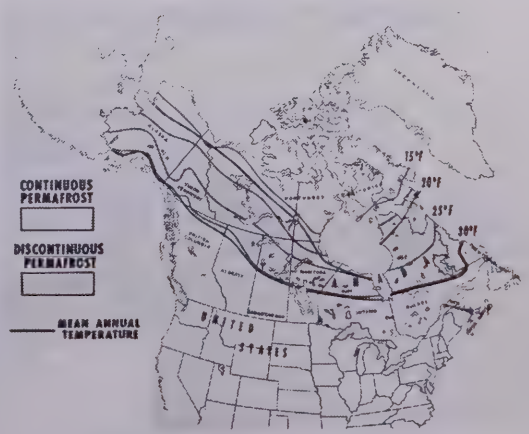


Fig. 6 Permafrost areas can create unique cementing problems

2000 ft (609.6 m) on the Alaskan North Slope. Shallow permafrost temperatures on the North Slope range from 15 to 27 F (-9.4 to 2.8 C). Hole enlargement while drilling may be a serious problem due both to melting and erosion. Drilling with ordinary rotary mud has caused so many problems that refrigerated salt-water polymer drilling fluid is now commonly used through the permafrost.

Cementing through the permafrost can result in specific problems. General problems depend mainly upon the type of permafrost. In the Arctic Islands, the formations tend to be fairly well consolidated so that thawing during drilling and cementing does not appear to be a major problem. The formation has sufficient strength and competency to maintain gage hole. Accelerated API Class A, C, or G cement with a slurry temperature of 50 to 60 F (10 to 15.6 C), preferably densified, could be used.

If the permafrost is incompetent and contains ice lenses, the requirements are: (a) prevent of hole enlargement due to melting and erosion while drilling; (b) use of a cement which will set at the low bore hole temperature without excessive heating of the mixing water or an unduly long WOC time; (c) the cement must set without excessive heat of hydration to prevent severe melting of the permafrost; and (d) adequate fluid time for placement.

Tests conducted by cement manufacturers, oil company and service company laboratories, with various types and formulations of cement slowly evolved into some standard test procedures and conclusions concerning cementing materials (5, 6, 7, 8, 9, and 10).

1 API Class A, C, or G cements are not suited for cementing through an unconsolidated permafrost zone although they may be used to good advantage where warmed mixing water and displacement fluids will not cause thawing problems.

2 Class G cement will freeze before it hydrates curing at 20 F (-6.7 C) with up to 4 percent Calcium Chloride accelerator, Table 1.

Table 1 API Class G Cement -- 44 Percent W/C Ratio

Calcium Chloride Per Cent	Condition After 24 Hours at 20°F	Compressive Strength - PSI 24 Hours at 20°F + 24 Hrs at 80°F
0	Frozen	535 (37.8 kg/cm^2)
2	Frozen	525 (37.1 kg/cm^2)
3	Frozen	645 (45.6 kg/cm^2)
4	Frozen	585 (41.3 kg/cm^2)

Table 2 API Class G Cement -- 44 Percent W/C Ratio

Calcium Chloride Per Cent	Compressive Strength - PSI Days at 20°F: Days at 80°F 0:1	1:1	3:1	7:1
0	3000 (212.0 kg/cm^2)	820 (58.0 kg/cm^2)	565 (39.9 kg/cm^2)	685 (48.4 kg/cm^2)
2	4500 (318.1 kg/cm^2)	890 (62.9 kg/cm^2)	860 (60.8 kg/cm^2)	715 (50.5 kg/cm^2)

Table 3 50-50 Calcium Aluminate Cement -- Fly Ash 10 Percent Salt by Weight of Water

Calcium Aluminate Cement	Permeability to Water Milidarcies
Lumnite	105.6
Ciment Fondu	56.5

Table 4 50-50 Calcium Aluminate Cement -- Fly Ash 10 Percent Salt by Weight of Water

Calcium Aluminate Cement	Temp. Rise °F*	Heat Capacity BTU/Lb/°F	Diffusivity Ft^2/Hr	Heat Transfer Coefficient BTU/Hr/Ft^2/°F/Ft	Heat Hydration BTU/Lb of Slurry
Lumnite	91 (32.8°C)	0.364 (0.364 Cal/gr/°C)	0.0094 (.1012 m^2/hr)	0.404 (.75 x 10^{-5} gram cal/sec/cm^2/°C/cm)	57 (31.7 gr Cal/gr
Ciment Fondu	143 (61.7°C)	0.374 (0.374 Cal/gr/°C)	0.0085 (.0915 m^2/hr)	0.375 (.69 x 10^{-5} gram cal/sec/cm^2/°C/cm)	92 (51.1 gr Cal/gr)

3 A cement which freezes and is subsequently warmed and hydrated will give a much weakened set with high permeability, Tables 2 and 3.

4 High aluminate cements liberate an immense quantity of heat upon hydration which might be detrimental to the surrounding formation, Table 4.

5 High aluminate cements are not stable to freeze-thaw temperature fluctuation, Fig. 7.

6 Gypsum-Portland cement blends were found to give better properties for cementing unconsolidated permafrost formations.

7 Fluid life of Gypsum-Portland Cement can be controlled by retardation from 30 min.

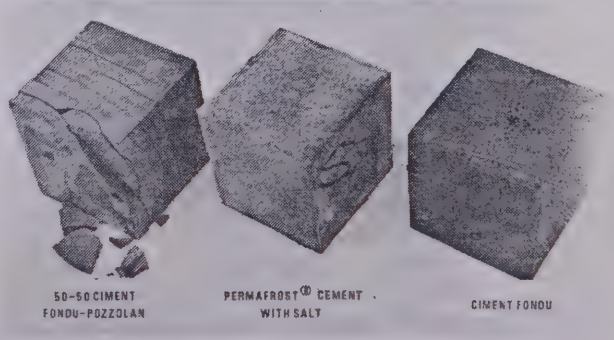


Fig. 7

Table 5 Gypsum-Portland Cement Slurry Fluid Life

Retarder Concentration lbs/sack	Circulating Temperature, °F 20° (-6.7°C)	30° (-1.1°C)	40° (5.0°C)
0.08	7:28	4:41	3:38
0.09	8:00	6:14	4:32
0.10	9:57	7:21	5:21
0.00	0:40	0:35	0:25

to over 4 hr with adequate strength development for continued well operations in 8 to 16 hr WOC time, Table 5 and Fig. 8.

In early 1971, an Arctic Task Group, working under the Committee on Standardization of Oil Well Cements of the American Petroleum Institute (API), began working on a tentative testing procedure to simulate the frozen conditions of the northern regions (13). More specific information was needed on special problems encountered with different types of permafrost. Depth and temperature of permafrost are influenced by topography, climate, vegetation, and type of formation. Seasonal temperature changes affect only the upper 50 to 100 ft (18.3 to 30.5 m). An active 1 ft to 3 ft (0.3 m to 0.91 m) surface layer covering the permafrost thaws in the summer and refreezes each winter (Figs. 9 and 10) (11, 12).

The API recognized the difficulties of adequately simulating arctic cementing conditions. To obtain more specific information, a task group surveyed operators on the North Slope. Reports on 37 separate operations were collected and the results tabulated (13). Then the task group surveyed laboratories of companies operating on the North Slope. Six reported having available test facilities for curing cements at low temperatures. Since there was little available data from tests at temperatures below 50 F (10 C), two cement

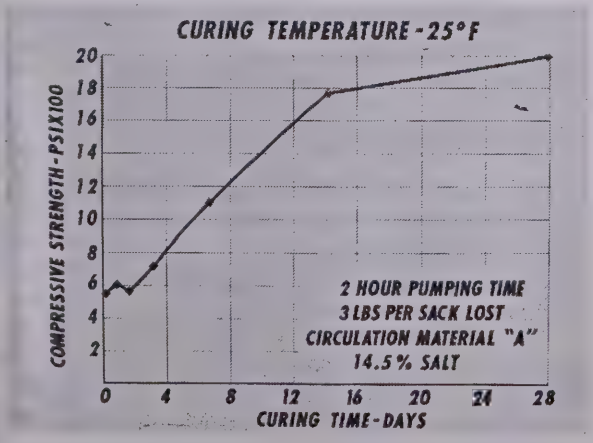


Fig. 8

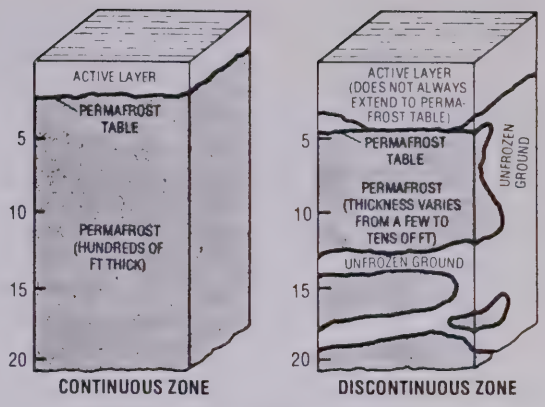


Fig. 9 Permafrost problems are further complicated with complex structures

test samples were distributed to participating laboratories to determine initial similarities among testing facilities. Based on the field survey and test results, a certain amount of standardization of laboratory facilities was achieved prior to establishing a standard testing procedure.

The two samples were tested for compressive strengths and thickening times. Thickening time tests were performed at 40 F (4.4 C), similar to surface mixing in winter operations, and strength test specimens were cured at 20 F (-6.7 C), fairly close to bottomhole temperatures found in permafrost. Test results among participating laboratories were comparable and closely matched field conditions.

The task group continued surveys of actual field operations including a request for advice on mixing, displacement, and curing

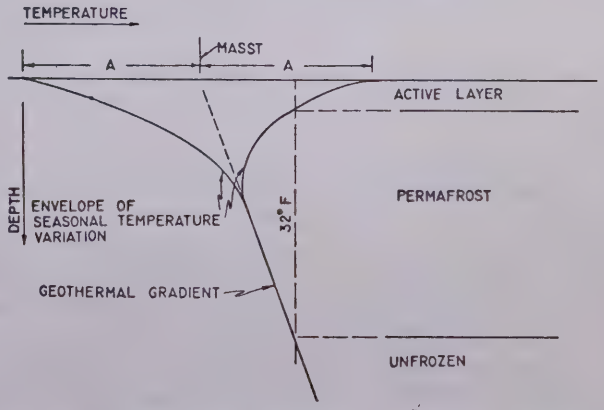


Fig. 10 Temperature envelope of natural thermal conditions. The slope of the geothermal gradient is distorted for clarity

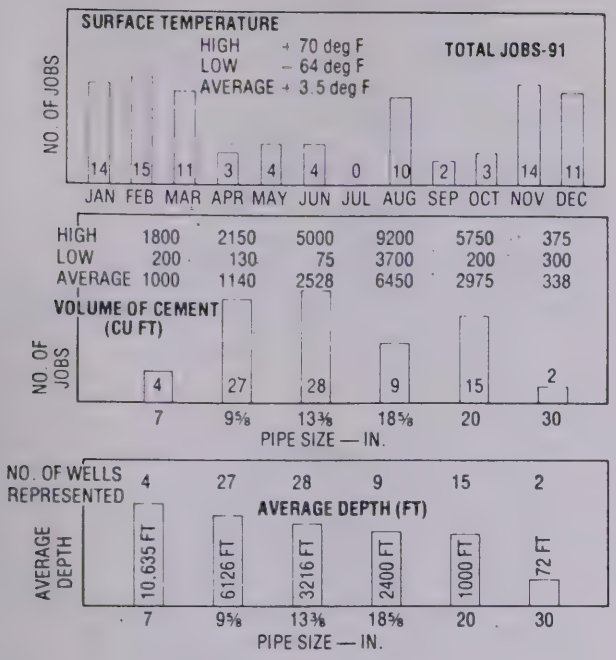

SURFACE TEMPERATURE
HIGH + 70 deg F
LOW – 64 deg F
AVERAGE + 3.5 deg F
TOTAL JOBS-91
NO. OF JOBS
14 15 11 3 4 4 0 10 2 3 14 11
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
HIGH 1800 2150 5000 9200 5750 375
LOW 200 130 75 3700 200 300
AVERAGE 1000 1140 2528 6450 2975 338
VOLUME OF CEMENT (CU FT)
NO. OF JOBS
4 27 28 9 15 2
7 9⅝ 13⅜ 18⅝ 20 30
PIPE SIZE — IN.
NO. OF WELLS REPRESENTED 4 27 28 9 15 2
AVERAGE DEPTH (FT)
AVERAGE DEPTH
10,635 FT
6126 FT
3216 FT
2400 FT
1000 FT
72 FT
7 9⅝ 13⅜ 18⅝ 20 30
PIPE SIZE — IN.

Fig. 11 Survey shows wide variations of arctic cementing jobs (13)

conditions (Fig. 11 and Table 6).

A basic outline for the cooperative testing program was formulated in October 1972. Two more tests, freeze stability and freeze-thaw cycling, were added to strength and thickening time test programs.

Freeze stability was tested because reports indicated that if setting cement was allowed to freeze before all water was hydrated, frozen water would create channels resulting in weak, porous cement.

Freeze-thaw cycling simulates operation of a well after cementing has been completed. Although permafrost formation temperature stays below freezing, formations below the permafrost usually are considerably warmed. Warm oil produced from below the permafrost heats the wellbore and thaws the cement. If a well is shut down for any reason, the permafrost will again freeze the cement. Cement compositions used, therefore, must withstand repeated freezing and thawing without much deterioration.

Table 6 Survey of Arctic Cementing Jobs (13)

Total Jobs: 91
Types of Cement Used: Class G Cement — 40 Jobs; PERMAFROST Cement — 37 Jobs; Cement Fondu — 10 Jobs; Class B Cement — 1 Job; Class C Cement — 1 Job; Other — 1 Job

Slurry Weight — Lb/gal — Total Jobs: 12-13 — 5; 13-14 — 2; 14-15 — 33; 15-16 — 42; 16-17 — 7; 17-18 — 1

Temperature of:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Water — deg F												
High	80	86	90	85	92	84	0	70	55	60	72	110
Low	– 6	60	50	42	91	82	0	35	50	Only temp	50	50
Average	37	79	70	64	91	83	0	53	53	recorded out of 3 jobs	61	80
Cement — deg F												
High	+15	+30	– 8	38	60	55	0	55	40	45	60	50
Low	–44	–38	–30	15	– 6	34	0	35	40	35	–18	–37
Average	–15	– 4	–11	27	27	45	0	45	40	40	21	7
Slurry — deg F												
High	60	80	59	62	62	58	0	60	50	60	65	58
Low	30	33	28	40	55	55	0	40	45	55	37	24
Average	45	47	44	51	59	57	0	50	48	58	51	41

Four test samples submitted by three companies were used in initial cooperative tests among ten laboratories belonging to Atlantic-Richfield, Amoco, Byron-Jackson, British Petroleum, Dowell, Exxon, Gulf, Halliburton Services, Lone Star Industries, and Mobil. Data collected from laboratory tests were in comparative agreement.

Based on results of these tests and further reports from field operations, the testing procedure was revised slightly.

Following further data collection and compilation, the task group modified the tentative testing procedure.

Results of a third series of cooperative testing produced a tentative arctic cementing testing procedure approved by letter ballot of Cement Standardization Committee members and published as Section 11 of API RP 10B: Recommended Practice for Testing Oil Well Cements and Cement Additives, Nineteenth Edition, January 1974. It was modified by a supplement issued in March 1976 and the tentative classification was removed in June 1976 (14).

TESTING PROCEDURE FROM API RP 10B (14)

11.1 Preparation of Slurry Samples. Prepare test samples according to Section 3 testing procedures, except that dry cement should be stored overnight in refrigerator at 20 F (-7 C). Ice water should be used in mixing slurry and in chilling the Waring Blendor container before using. Slurry after mixing should be 40 F (4 C) ± 2 F (±1 C) and temperature should be measured and reported on all tests.

11.2 Water Requirement. Mixing water is to be expressed on the basis of 100 parts of solids.

11.3 Thickening Time. Thickening time test is to be performed on an atmospheric pressure consistometer at 40 F (4 C).

11.4 Strength. Cure under atmospheric pressure at 20 F (-7 C) and 40 F (4 C) for desired testing period, i.e., 1-3-7 days.

Selected cementing compositions should be pumped for 1 1/2 hr on an atmospheric pressure consistomer before pouring into cube molds for curing. Curing environment below 32 F (0 C) should be in air or in a container of fresh water placed in an ethylene glycol batch.

Example: For 24-hr strengths:

(a) Pump 1 1/2 hr at 40 F (4 C) and atmospheric pressure.
(b) Cure slurry for 22 hr at 20 F (-7 C) or 40 F (4 C).
(c) Remove molds 30 min. before breaking and store at 40 F (4 C) under water.

11.5 Freeze-Thaw Cycling at Atmospheric Pressure. Slurry should be prepared as in Par. 11.1 and cured under the following cycle: (It is suggested that the cycle begin on a Monday)

(a) 48 hr at 40 F (4 C) Monday
(b) 24 hr at 20 F (-7 C) Wednesday
(c) 24 hr at 40 F (4 C) Thursday
(d) 72 hr at 100 F (38 C) Friday
(e) 72 hr at 170 F (77 C) Monday
(f) 24 hr at 100 F (38 C) Thursday
(g) 72 hr at 20 F (-7 C) Friday
(h) Raise to 40 F (4 C) and repeat cycling on Monday.

11.6 Strength cubes should be examined and broken after 1 and 3 cycles under these conditions (14 days and 42 days). Cure all strength specimens under water in molds during cycles with top of cement exposed to water. Break control test specimens after 48 hr at 40 F (4 C) for references.

An alternate procedure would be to completely remove the cement strength specimens from molds in 48 hr at 40 F (4 C) and immerse the unconfined cement cubes in fresh water for freeze-thaw cycling.

Deviations from the recommended API Procedure can be made when circumstances so warrant. For example, a Berea sandstone block 6 in. x 6 in. x 12 in. (15.2 x 15.2 x 30.4 cm) was cored to a depth of 11 in. (27.94 cm) with a 3-in. (7.62-cm) core barrel. The core hole in the sandstone block was 3 1/4 in. (8.26 cm) dia. A length of 1-in. (2.54-cm) line pipe was then placed in the center of two of the four cored blocks. Slurries of API Class G and Gypsum-Portland Cement were poured into the cored holes. The samples were then subjected to the freeze-thaw cycle recommended procedure of the API. Coincident with the sandstone test, a simulated unconsolidated permafrost was prepared by freezing a slurry of water, sand and pea gravel around a piece of pipe. The pipe was then warmed and slipped out of

Fig. 12

Fig. 13

the frozen formation and the hole filled with the Gypsum-Portland Cement slurry. These samples also were subjected to the same freeze-thaw cycles.

Results of these tests are shown as Figs. 12 and 13. Note that the Class G Cement contained such sufficient unreacted moisture that the freeze-expansion cracked the sandstone. The Gypsum-Portland Cement shows no damage.

CONCLUSIONS

1 A survey of operating conditions in cold and arctic areas has been made.

2 A testing procedure for simulating cold and arctic conditions has been formulated.

3 Cementing materials have been tested and evaluated under arctic conditions both in the field and in the laboratory.

4 Deviations from the recommended test procedures may be made.

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